

## Introduction to Effects of Urbanization on Stream Ecosystems

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*Abstract.*—The human population of the earth continues to grow, with most of that growth occurring by expansion of existing urban areas. The resulting conversion of rural land to urban land uses will affect associated streams. This book provides researchers, aquatic resource managers, land use planners, and others with results of recent studies of the effects of urbanization on stream ecosystems. In this introductory chapter, we review some of the existing literature on urbanization and highlight some issues addressed by other chapters of the book. We expect the information in this book will be helpful to new and established researchers studying effects of urbanization, as well as to managers and others interested in recent progress in the field. Communicating results of scientific research to managers and planners is essential if streams are to be protected as urban populations continue to grow.

The world's ecosystems provide a wide range of essential and economically valuable services (Costanza et al. 1997). Aquatic ecosystems provide a wide array of such services, including freshwater for agricultural, industrial and municipal uses, transportation corridors, food, opportunities for recreation and esthetic enjoyment, and waste disposal (Petts 1989). As human populations have grown, their effects on aquatic ecosystems have increased (Postel 1996, 2000; Vitousek et al. 1997; Sala et al. 2000). Freshwater ecosystems are particularly vulnerable because human populations are concentrated near waterways (Sala et al. 2000; Alberti and Marzluff 2004).

The world's urban population is increasing at a faster rate than the total population. Almost all population growth in the next 30 years is expected to occur by expansion of existing urban areas (United Nations

2004). The world's urban population was estimated to be 3 billion in 2003 and is expected to increase to 5 billion by 2030 (United Nations 2004). As rural lands surrounding urban areas are converted to urban land uses, nearby freshwater systems will experience increased stresses with a variety of consequences for biodiversity and ecosystem processes (McDonnell and Pickett 1990; Sala et al. 2000; Paul and Meyer 2001).

Previous studies have identified a wide variety of stressors affecting streams in urban areas (Paul and Meyer 2001). Urbanization can change the chemical and physical properties of stream systems (Klein 1979; Heany and Huber 1984). Large areas of impermeable surface can increase the frequency and magnitude of storm flows (Arnold et al. 1982; Booth and Jackson 1997; Trimble 1997). Excessive groundwater pumping and reduced recharge lessen base flows (Klein 1979; Finkenbine et al. 2000) and can exacerbate the effects of droughts. Modification of stream hydrology and flood management practices can alter the sedi-

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ment regime, with subsequent effects on streambed composition, and stream channel morphology (Arnold et al. 1982; Booth 1990, 1991; Booth and Jackson 1997; Finkenbine et al. 2000). Loss of riparian vegetation can increase water temperatures as stream shading is reduced (Booth 1991; Belt and O'Laughlin 1994; LeBlanc et al. 1996), reduce habitat structure for fish (Martin et al. 1986; Finkenbine et al. 2000), and change trophic processes (Kellar and Swanson 1979; Vannote et al. 1980). Concentrations of nutrients, pesticides, organic chemicals, and heavy metals are often elevated in urban runoff and treated wastewater, which are major sources of water in many urban streams (Klein 1979; Heany and Huber 1984; Field and Pitt 1990; Ahel et al. 2000; Lieb and Carline 2000; Shinya et al. 2000). These changes in physical habitat and water quality have been linked to changes in aquatic biota. Urban stormwater runoff has been recognized as an important factor affecting biota (Heany and Huber 1984), as have hydrologic and land use changes associated with urbanization (Weaver and Garman 1994; Wichert 1994, 1995; Finkenbine et al. 2000; Wang et al. 2000; Sonneman et al. 2001; Walsh et al. 2001; Wang and Lyons 2003). Understanding the effects of these stresses on aquatic assemblages will be extremely important in preserving, rehabilitating, and managing these ecosystems as urbanization proceeds (Nilsson et al. 2003; Cottingham et al. 2004).

This book provides researchers, aquatic resource managers, land-use planners, and others with results of recent studies of the effects of urbanization on stream ecosystems. The book includes case studies from all regions of the United States and one from Brazil. The studies in the United States encompass a variety of environmental settings, ranging from arid, highly urbanized Southern California to the humid southeastern and long-urbanized northeastern United States. Regional comparisons of the characteristics of urbanization and effects of urbanization on biological assemblages based on a standard study design are also included. Other studies address a range of topics, including hydrology, economics, and management and offer a variety of tools that will be useful to others embarking on studies of urban streams.

### What Is Urbanization?

The most basic definition of urbanization is the transformation of land from rural land uses, such as agriculture, to urban land uses, such as housing. However, summarizing the many environmental effects of ur-

banization as a variable in scientific studies is less straightforward. Popular surrogate measures for urbanization in the recent literature include general measures of urban land use, population density, and the extent of impervious surface (Arnold and Gibbon 1996; Center for Watershed Protection 2003; Morse et al. 2003). Use of impervious surface has been especially favored because it is linked to changes in stream hydrology, which affect stream biota and a variety of stream processes (Poff et al. 1997; Konrad and Booth 2005, this volume). However, urbanization clearly has a variety of interacting effects on stream ecosystems that may be further influenced by regional and historical differences in urban development and natural factors such as climate, physiography, geologic setting, vegetation, and soils (Harding et al. 1998; Fitzpatrick et al. 2004 and 2005, this volume). Tate et al. (2005, this volume) use an urbanization intensity index originally formulated by McMahon and Cuffney (2000) to describe the characteristics of urbanization in specific study areas. Information on the specific characteristics of urbanization in particular geographic areas is especially important as researchers and resource managers try to extrapolate results of studies from smaller to larger geographic scales. Coordinated studies by Meador et al. (2005, this volume), Cuffney et al. (2005, this volume), and Potapova et al. (2005, this volume) highlight similarities and differences in responses of biotic assemblages to various characteristics of urbanization in different regions of the United States. Some of the variability observed is likely due to the fact that patterns of urbanization and environmental manifestations of those patterns are not necessarily the same from areas with different economic, social, and environmental conditions. The study by Pompeu et al. (2005, this volume) is instructive in this respect. In Brazil, environmental scientists are dealing with urban problems such as disposal of raw sewage that have been greatly reduced in the United States since implementation of the Clean Water Act. Thus, the results of studies in Brazil and the United States should only be applied across areas with caution and recognition of the similarities and differences in the characteristics of urbanization in each location.

### Approaches to Studying the Effects of Urbanization

As in many other areas of stream ecology, studies of the effects of urbanization are often observational and correlative. In fact, it is difficult to imagine doing an experimental study of urbanization. Studies in this book

and the literature take several approaches. In one approach, urbanization is considered a single factor and streams or stream reaches with different levels of urbanization are sampled. Biotic assemblages or other biological measures at the sampling sites are analyzed in terms of that single factor to infer effects of urbanization. In another approach, biotic assemblages or metrics are ordinated, correlated, or regressed against a variety of physical and chemical environmental factors, often including the original measure of urbanization used to design the study. Significant environmental factors are then related back to urbanization using similar correlative methods. These approaches have clearly been useful, because they form the basis of much of our existing knowledge. However, one must be cautious when generalizing across a variety of spatial scales based on individual studies with different designs (Kennen et al. 2005, this volume).

Tate et al. (2005) offer one approach to this problem by applying a single study design to studies of the effects of urbanization in three different United States cities—Birmingham, Alabama; Boston, Massachusetts; and Salt Lake City, Utah. A standard protocol based on an index of urban intensity (McMahon and Cuffney 2000; Tate et al. 2005) was applied to site selection within the three cities. There was some flexibility in the final site selection and study design to account for regional environmental differences. For example, in Salt Lake City, Utah, there were few perennial streams for study because of the arid climate and a correlation between urbanization and altitude. These factors required a partially nested design (multiple sites per stream), in contrast to single-site per stream designs in the other two cities (Tate et al. 2005). Standardized sampling of stream habitat (Short et al. 2005, this volume), benthic algae (Potapova et al. 2005), benthic macroinvertebrates (Cuffney et al. 2005), and fishes (Meador et al. 2005) provided convincing comparisons of stream ecosystem responses among the three cities. Integration of the results of these studies is proceeding as the approach is applied to additional regions within the United States (Cathy Tate, U.S. Geological Survey, personal communication). Although other approaches are certainly possible, these studies represent a step toward the types of interdisciplinary efforts necessary to forecast effects of urbanization on stream ecosystems in support of proper planning and management (Benda et al. 2002; Nilsson et al. 2003).

By design, studies in this book mainly approach the effects of urbanization by assessing changes in biological assemblages. Biological assemblages are sensitive indicators of stream environmental condi-

tions, and biotic indices are efficient ways of assessing stream condition (Karr 1991; Karr and Chu 1999; Simon 2003). However, there are many approaches to assessing effects of urbanization. Historical reconstructions of stream condition during the early stages of development are possible given sufficient historical data (MacCoy and Blew 2005, this volume). Monitoring growth and life history characteristics of fishes can be informative (e.g., Fraker et al. 2002). Limburg et al. (2005, this volume) use eastern blacknose dace *Rhinichthys atratulus* as a sentinel species to monitor inputs of anthropogenic nitrogen using stable isotope analysis in New York watersheds. Erickson et al. (2005, this volume) use several physiological endpoints to assess stress in fishes related to urban runoff. Advances in genomic tools, such as genetic microarrays (Rotchell and Ostrander 2003; Williams et al. 2003), make it possible to determine if organisms exhibit physiological responses to pollutants. In combination with passive samplers to assess the presence of hydrophobic and hydrophilic pollutants (Huckins et al. 1993; Alvarez et al. 2004; Petty et al. 2004; Rowe et al. 2005; Rosen et al., in press), these techniques provide sensitive indicators of organism exposure to chemicals in urban runoff, beyond toxicity tests or chemical measurements of pollutant concentrations.

Indices of biotic integrity (IBIs) are a common method of assessing biotic responses to environmental stressors, including those associated with urbanization. Typically, IBIs compare index scores to a set of reference sites that represent the least disturbed condition (Karr 1991; Karr and Chu 1999; Simon 2003); however, it is often difficult to define useful reference sites. Carter and Fend (2005, this volume) apply new concepts to determining the best attainable conditions in urban areas where highly urbanized areas might not be expected to have as high a potential for ecological function as less intensively urbanized areas or areas experiencing different types of urbanization (low-density housing versus intense industrial development). In contrast, MacCoy and Blew (2005) present an example of how to use historical land survey notes to describe ecological conditions before major development occurred. Many recent studies have identified the level of watershed development at which ecological effects become evident (e.g., Wang et al. 2000; Walsh et al. 2001; Morse et al. 2003; Taylor et al. 2004). These studies hint at a more basic issue confronting managers of urban streams. What ecological services do we expect from urban streams, and how likely is it that we can protect or rehabilitate those services in urban streams?

Studies of urban streams typically focus on the form of stream responses to urban influences. Few studies have addressed the equally difficult question of what services society expects from urban streams and how much effort society is willing to expend to protect healthy streams or to rehabilitate degraded streams so they can provide the expected services. Cottingham et al. (2004) identified the lack of quantification of urban stream ecosystem goods and services as a key knowledge gap. Society is willing to expend time and money to preserve urban waterways (Dumas et al. 2005; Winternitz and Holtz 2005; both this volume) and even very highly urbanized areas, such as Southern California, can have streams with some (and often interesting) ecological function (e.g., Brown et al. 2005a; Burton et al. 2005; Lin and Ambrose 2005; all this volume). Preserving the ecological values of waterways in the face of other societal needs is difficult and requires aquatic resource scientists and managers to participate in interdisciplinary efforts that extend beyond traditional ecology and integrate topics such as economics, engineering, and the social sciences (Postel 2000; Nilsson et al. 2003). Dumas et al. (2005) introduce a number of economic methods for determining the value of ecosystem services. Winternitz and Holtz (2005) provide a case study of an ongoing and complex negotiation focused on protecting the fisheries resources of an urban California river. As these examples demonstrate, participation in interdisciplinary efforts will be challenging, especially given discipline specific knowledge gaps and mismatches of spatial and temporal scale among disciplines (Benda et al. 2002; Nilsson et al. 2003). However, integrated approaches to understanding and managing urban streams provide the greatest opportunity for developing robust, sustainable solutions.

## Conclusion

Articles in this book provide invaluable background for anyone involved in or interested in urban streams. Although our knowledge of urban streams is improving, there are still considerable challenges to understanding these systems and managing them effectively (Cottingham et al. 2004). Additional studies are needed to document similarities and differences in the characteristics of urbanization and the effects of urbanization on stream ecosystems across multiple spatial scales. Differences in socioeconomic conditions between regions and countries likely affect both the valuation of stream ecosystem services and the ability to protect and rehabilitate them (Cottingham et al.

2004). Perhaps most important and most challenging and one of the principal motivations for this book, the scientific knowledge of aquatic resource scientists and managers must be made accessible to urban planners so that streams can be protected as urbanization occurs rather than attempting to rehabilitate them afterward (Karr and Chu 1999; Nilsson et al. 2003; Cottingham et al. 2004). As our knowledge improves, so will our ability to protect and rehabilitate urban streams and the valuable services they provide to urban populations.

## Acknowledgments

We thank Tom Cuffney and James Carter for comments that significantly improved this manuscript. Larry Brown and Mike Meador were funded by the National Water Quality Assessment Program of the U.S. Geological Survey, during the preparation of this article. Bob Hughes was partially funded by grant #R-829498-01 from the National Center for Environmental Research (NCER) STAR Program of the U.S. Environmental Protection Agency.

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